NEW CAPACITIVE-ARRAY SENSORS FOR POST-PROCESS CURE VERIFICATION AND NDE OF POLYMERS AND COMPOSITES

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INTRODUCTION

A new capacitive array sensor has been developed for process verification and NDE of polymers and composites. Unlike existing dielectrometer technology, the new sensor incorporates several innovations to maximize sensitivity to material properties while minimizing the effects of temperature, humidity and electromagnetic interference. Conventional dielectric measurement systems require sensors to be embedded within a material and discarded after a single use. Furthermore, conventional sensors are so sensitive to environmental variables that cure monitoring is based solely on changes in the material ionic conductivity; no absolute measure of cure state is possible. The configuration of these new sensors greatly reduces sensitivity to environmental variables and permits external, rather than embedded, measurement making both post-process cure verification and NDE possible. Since the sensor is not discarded, the cost per measurement is greatly reduced.

CAPACITIVE ARRAYS FOR SENSING APPLICATIONS

A capacitive array is a set of two or more electrodes arranged to generate an harmonic fringe electric field as shown in Figure 1. In the simplest cases such devices can be used as proximity and humidity sensors [1]. The most common application of such sensors in materials characterization is the cure monitoring of polymers and polymer-matrix composites. This application, while arguably more sophisticated than a humidity sensor, is inherently qualitative and the sensor configurations entirely unsuited to NDE applications.

THE DIELECTROMETER FOR CURE MONITORING

Capacitive array sensors used to monitor curing of polymers and their composites are typically referred to as dielectrometers. The reason for this naming convention is that cure monitoring systems are based on the measurement of changes in the polymer's dielectric

properties. The property which dominates theses measurements is the ionic conductivity. As the polymer cures, the ionic mobility is reduced and the capacitance of the material increases. At full cure the increase in the capacitance plateaus and the system terminates the cure process.

The cure monitoring process is ideal in that it does not require a quantitative, repeatable measurement. Since the sensors are typically embedded in the part, the orientation of noise sources is fixed during the entire measurement process. Embedding the sensor also allows the sensor to interrogate material on both sides of the interdigitated electrodes.

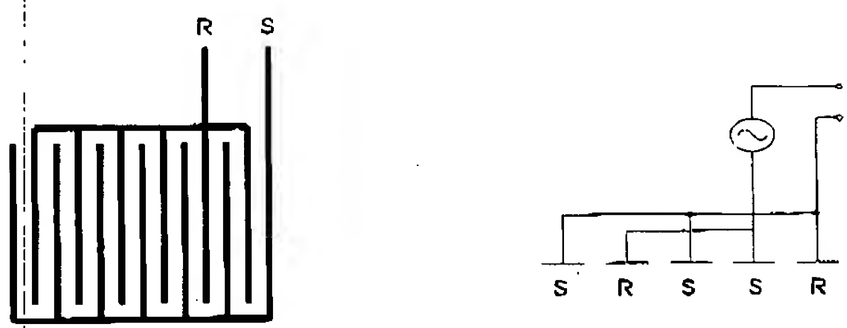

Figure 1. Simplified configuration of a typical interdigitated capacitive array sensor. S and R indicate source and receiver electrodes.

CAPACITIVE ARRAYS FOR CURE VERIFICATION AND NDE OF COMPOSITES

Unlike the simplistic case of cure monitoring, the application of capacitive arrays to post process cure verification and NDE of composites presents numerous noise and repeatability problems. Although strides have been made in characterizing the noise associated with sensor lift-off [2], little progress has been made with respect to material-induced and environmental noise sources. In the course of this work, three significant modifications to conventional capacitive arrays were implemented which permit single-sided, quantitative and repeatable measurements to be performed on both polymers and composites.

In the ideal case, a capacitive array is used to measure the properties of a dielectric material which can be approximated as a capacitor. The presence of electrical constituents,

however, results in an equivalent circuit that contains a relatively small resistor. In order to be sensitive to the changes in the capacitive portion of the material a high resolution phase detector is needed. In the system described, an embedded phase and gain electronics system which provided 0.2 degree phase-shift sensitivity was used.

The elastic anisotropy of composites allows both materials and structures to be designed with optimal properties for a given applications. This anisotropy, however, presents many challenges to traditional NDE techniques. In the case of composites with conductive constituents, such as graphite fibers, it also results in an electrical anisotropy. Since conventional capacitive array sensors have either a two-fold or four-fold symmetry in their applied field [3-5], the sensor output changes as the sensor is rotated with respect to the conductive fibers in a composite making repeatable measurements difficult at best.

To overcome the problem presented by the electrical anisotropy of graphite reinforced composites, TPL used electrodes in a concentric circle arrangement. This patented electrode arrangement produces a field with equal components in all directions. The result of such an arrangement is that the sensor is insensitive to rotation with respect to the graphite fibers in the composite.

Environmental variables also strongly affect the output of a capacitive sensor. Changes in both humidity and temperature will hinder repeatable measurement. To overcome this problem TPL implemented a differential detection scheme which provides common mode rejection. In this configuration, two capacitive arrays are used. One array is used to sample environmental changes, while the other is used to interrogate the material under test. Both the gain and phase of the two sensors is then detected in a differential mode to greatly reduce the effects of environmental changes.

DETECTION OF HEAT INDUCED DAMAGE IN COMPOSITES

The new capacitive array sensors were used to evaluate composite test panels exposed to high heat fluxes. The test panels were fabricated by Wright Laboratory using an AS4/3501-6 cloth in an eight ply, quasi-isotropic layup. The test panels were exposed to a quartz filament heat source at a variety of temperatures and exposure durations. Portions of the panels were then destructively tested to determine the level of degradation caused by the heat exposures. Phase and amplitude data from the new capacitive array sensor is shown for a control sample and two damaged samples in Figure 2. Of particular note is the difference in sensor response with respect to the type of heat exposure. The sensor is clearly more sensitive to the longer exposure and lower temperature. This can be explained by the fact that such an exposure affects a larger volume of material, whereas short, hotter exposures tend to cause damage in the near surface.

DETECTION OF FABRICATION DEFECTS IN COMPOSITES

The ability of the new sensor to detect laps, gaps and voids in composite was also investigated. Lap and gap samples were AS4/3501-6 tape, 16 layers in a unidirectional

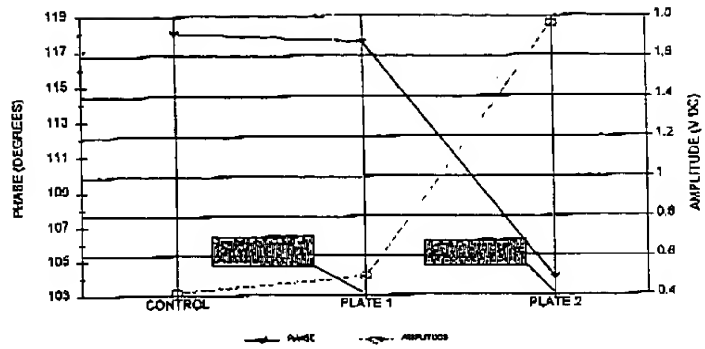

Figure 2. Phase and amplitude output of the capacitive array sensor on composite samples exposed to varying levels of heat flux.

layup. Laps were created by omitting two layers during layup from a specified internal point to an edge. Gaps were created by omitting a .125" wide section, two layers thick within the sample. All defects were centered about the mid-ply of the composite. High void content panels were created by improperly curing the part. Lap, gap and void defects were verified using standard ultrasonic C-Scans.

Using a three-axis scanning system, two dimensional, C-scan images of the magnitude of the electrical impedance measured by the probe were generated. The probe successfully detected and imaged laps, gaps and high void content regions in the test samples. Figures 3 and 4 show scan results.

Figure 3. Electrical impedance C-Scan of a composite panel with two-layer lap (lower) and gap (upper) defects.

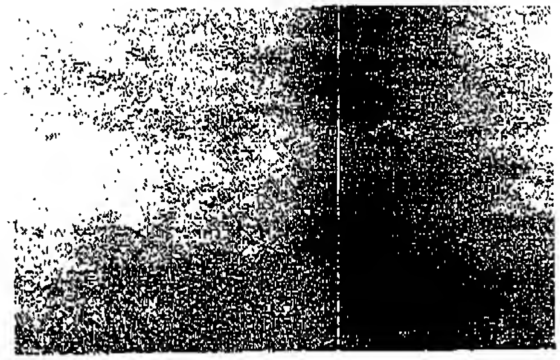

Figure 4. Electrical impedance C-Scan of a composite panel with a high void content region (dark area).

POST-PROCESS CURE VERIFICATION OF PHENOLIC PARTS

The capacitive array sensor was used to identify the state of cure of phenolic parts provided by Delphi Chassis Systems. The test part is the output rod of a brake booster system used in automobile braking systems. The part fabrication process includes a post-cure step which is critical to the structural integrity of the part. Since there are no visible differences between the post-cured part and parts which have not been post-cured, it is useful to have an automated means for identifying and rejecting improperly cured parts.

TPL evaluated a total of four lots of phenolic parts with two configured in each of two geometries. The evaluation was blind. All but one part were matched to the suppliers grouping using the capacitive array. Both TPL and the supplier suspect that the unmatched part is, in fact, defective as there is no other protocol for separating these groups save for destructive testing. Figure 5 is a photograph of the parts supplied and two of the capacitive array prototypes. Figures 6 and 7 show sensor output for each of the groups of phenolic parts.

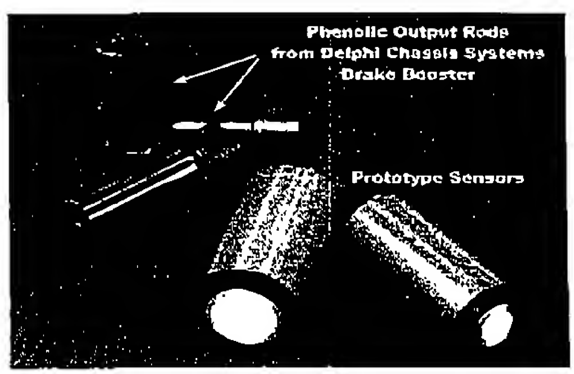

Figure 5. Phenolic output rods and two capacitive array sensor prototypes used in these studies.

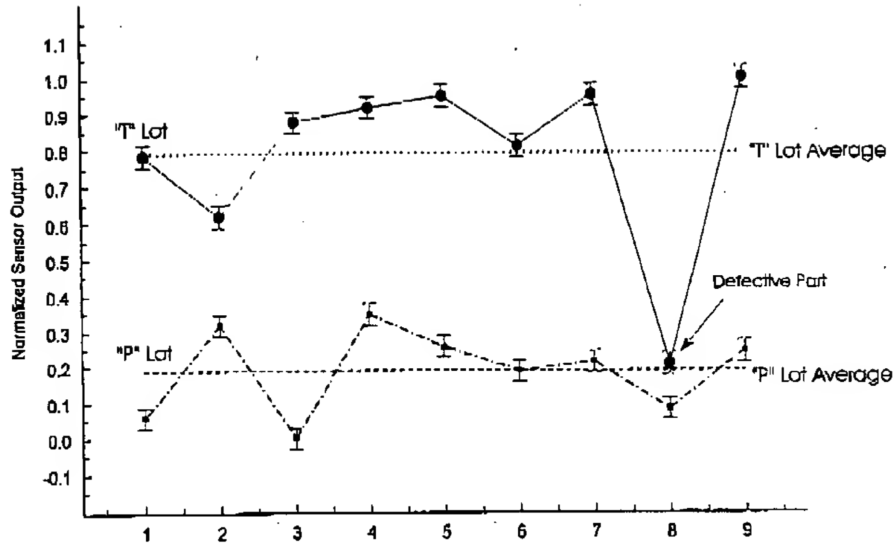

Figure 6. Capacitive array sensor separation of phenolic auto parts with geometry B. The "T" lot part, grouped with "P", appears to be improperly cured.

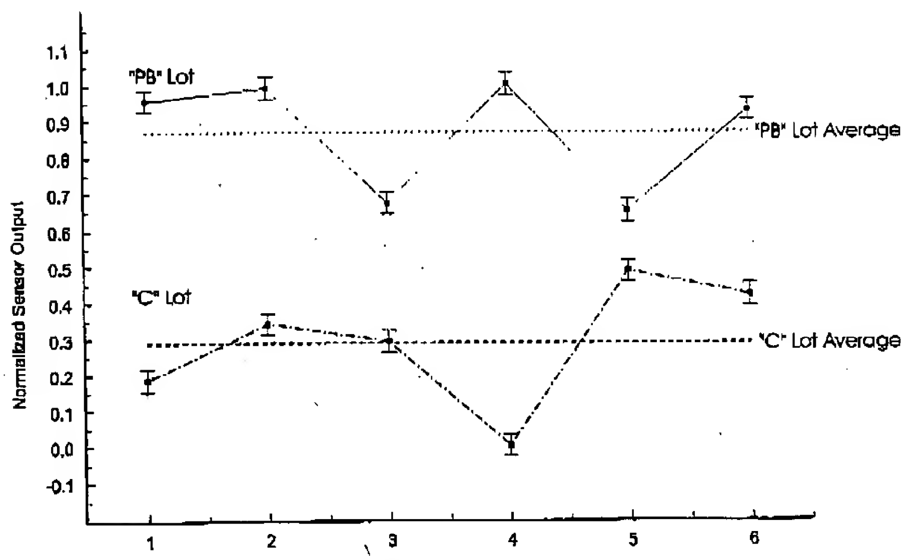

Figure 7. Capacitive array sensor separation of phenolic auto parts with geometry A.

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